

Research of Li_4SiO_4 irradiation tritium production device

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Abstract Tritium self-sustain and circulation is the core problem to use fusion energy peacefully. As the core component of the breeder in-pile irradiation test, the irradiation tritium production device provides irradiation space for breeders' tritium production and release. We take the Li_4SiO_4 as the research object and design the structure of the irradiation device. We complete the physical parameters computation, the irradiation device safety analysis and the flow field analysis of the breeder refueling, realizing the adjusting of the breeder irradiation temperature and the tritium release temperature window and making the control of gas operational parameters come true. The data could provide reference for breeders' in-pile irradiation research.

Key words Li_4SiO_4 , Breeding, Tritium Production, Irradiation Device, Design

1 Introduction

With the rapid development of society, energy issue has become the focus of globe interest. Fusion energy is an effective way to solve the energy poverty which whole human society had faced for years. Tritium self-sustain and circulation is the key to achieve fusion energy's mass-application. Now, we lack of enough neutron resource power to accomplish tritium fusion. To found a tritium production line in the thermal neutron reactor and experiment with breeder material irradiation is the best way to explore the regularity of tritium production and release.

Li_4SiO_4 and Li_2TO_3 are both on the list of fusion reactor breeder materials. With high content of Li, low neutron activation, good performance of tritium output, Li_4SiO_4 has become the preferred choice as TBM tritium breeder coating in EU and China.

In this research, we take Li_4SiO_4 ceramic ball as the research object to design the irradiation device. The tritium production device, which provides irradiation space for Li_4SiO_4 breeder ball, is the key component of tritium production line.

2 Structure of tritium production device

As the key facility of tritium production line, tritium production device is made up of inside and outside irradiation cylinder, conveyer device, electrical heating device, thermal-couple, probe, ventilating arrangement etc. the carrier gas enters the lower chamber through the horn mouth of the center pipe at first, then turns 90° in irradiation bin and flows into the upper gas chamber, at last it flows into collection and analysis facility through the gas exit. The part between outside and inside irradiation cylinder is called gas temperature adjustment area. Cooling gas enters temperature adjustment area from the bottom of this part and controls irradiation temperature of breeder. Fig.1 shows the structure of irradiation tritium production device.

Tritium production device has the structure of double-side irradiation cylinder shell and nonlinear electric heating facility, all parts orientate to the center axis. We take irradiation heat, isothermal effect of heat-expanding and cold-shrinking, heat compensation into consideration, making temperature of breeder evenly distributed. Intake-pipe and drive-pipe are connected on the top of reactor which makes tritium

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production device easy to move. The pipes before and after the connecting box are separately covered with stainless steel and plastic bellows (Fig.1).

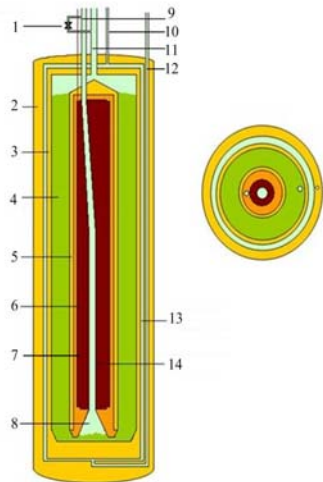


Fig.1 Structural drawing of CITP-II tritium production irradiation device. 1. Switch valve; 2. Outside irradiation cylinder; 3. Inside irradiation cylinder; 4. Breeder material; 5. Electrical heating facility; 6. Thermalcouple; 7. Mgo core cylinder; 8. Horn mouth; 9. Carrier gas intake-pipe; 10. Cooling-gas escape-pipe; 11. Carrier gas escape-pipe; 12. Cooling gas intake-pipe; 13. Cooling gas room; 14. Center pipe.

3 Parameter detection of tritium production device

The tritium production device has a system to accomplish the measurement and monitoring task. Main monitoring targets are: neutron flux, temperature, gas flux, pressure etc. Main measurement parameters are: neutron flux, 2: inner temperature of irradiation device, 7; carrier-gas flow, 2; cooling-gas flow, 2; carrier-gas pressure, 4; cooling-gas pressure, 2; current of electric heating facility, 2; breeder loading height, 3.

4 Calculation of tritium production device

Physical properties, thermodynamic engineering performance, tritium output capacity are influenced by the structure and materials of tritium production device. The feasibility of tritium production device depends on realizable refueling of the breeder. A series

of iterative calculations of physic, thermo-dynamic, flow field and structural strength had been implemented to improve and optimize the design of tritium production device.

4.1 Calculation of physical parameter

We have established a computation model of tritium production device based on the reactor core physical calculation model, obtaining physical parameters and varying patterns in different positions through the calculations of self-shielding factor, neutron spectrum, neutron filling rate and tritium output distribution with different neutron energy levels. Calculation model of tritium production device is a concentric cylinder with stainless steel coating, other parameter are: helium as cooling-gas; diameter of Li_4SiO_4 breeder ball, 1 mm; ^6Li content, 7.5%; clearance rate of breeder ball, 20%; breeder loading height: 750mm; weight, 1132 g.

Self-shielding factor: Self-shielding factor is influenced by the structure, materials and the location of the irradiation device. Thermal neutron self-shielding factors are 0.438, 0.387, and 0.393, respectively, when the irradiation device located in active area. Thermal neutron factors are 0.554, 0.565, 0.538, and 0.528 when irradiation device is located in 12#, 15#, 2#, and 4# channel of heavy water reflection area. Average self-shielding factor in active area is less than in heavy water reflection area.

Neutron flux: Average neutron flux will be influenced by the location of tritium production device. There are two things causing this change: one is that Li_4SiO_4 will reduce neutron flux as a neutron capturer, another is that the self-shielding of Li_4SiO_4 breeder will cause neutron flux lower. We can see the obvious changes of average neutron flux after tritium production device fixed in reactor from Table 1. Tritium production device in H4, G8, or in channel 12#, 15#, 2#, 4# of heavy water reflection area has the same effect compared as it is in B1.

Table 1 Changes of average neutron flux

Category (energy)	Flux before loading (n / $\text{cm}^2 \text{ s}$) $\times 10^{13}$	Flux after loading (n / $\text{cm}^2 \text{ s}$) $\times 10^{13}$	Percentage of surplus (%)
Thermal neutron (<0.625 eV)	6.06	0.798	13.2
Epithermal neutron (0.625 eV– 5.53 KeV)	3.22	2.73	84.8
Fast neutron (5.53 eV–20 MeV)	3.61	3.52	97.5

Productivity of tritium: The productivity of tritium is affected by the thickness of Li_4SiO_4 breeder and location of irradiation tritium production device. On one hand, thin loading layer will cause low productivity of tritium and could not support the on-line measurement and test. On the other hand, thick loading layer also will cause low productivity of tritium because of the big thermal neutron absorption section of ^6Li . Different productivities of tritium with different thicknesses of breeder layers in B1, H4 and G8 in Fig.2. The output of tritium varies with the thickness of Li_4SiO_4 layer and the productivity of tritium is different with different breeder locations even with same thickness.

The best loading thickness does exist in different locations if the loading thickness is over 2mm, while the productivity does not change too much, and increasing the content of ^6Li is a good way to improve the productivity of tritium.

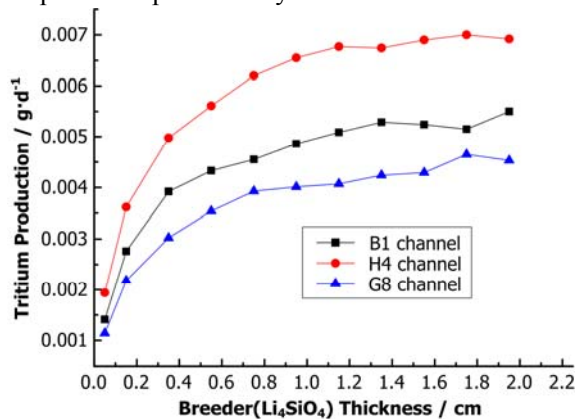


Fig.2 Tritium production with different breeder thicknesses.

^6Li and ^7Li have different neutron absorption sections, which effects tritium productivity. Neutron flux and thermal neutron flux change very much in different locations. Through calculation of productivity of tritium in location B1, H4, G8 and channel 12#, 15#, 2#, 4# with the same loading thickness, we can suppose that: the quantity of tritium produced by ^7Li in the reactor core is about 10^2 times of that in the heavy water reflection area. However, the quantities of tritium produced by ^6Li in these two areas are very close. The tritium production capacity by ^6Li is about 10^3 times of ^7Li , which shows the productivity of tritium will be great if the content of ^6Li is improved.

4.2 Calculation of thermodynamics

Heat source of the tritium production device has two main parts, the heat released by the structure material in n- γ radiation field and the heat released by breeder when it absorbs neutrons. The thermal neutron flux is $6.06 \times 10^3 \text{ n/cm}^3$, the weight of Li_4SiO_4 is 1132 g, heating efficiency of outer irradiation cylinder, the inner irradiation cylinder is 325 W and Li_4SiO_4 is 375 W, 325 W and 7 320 W, respectively. There are three ways of tritium production device cooling: 1. heat radiation released by the tritium production device itself; 2. gas cooling; 3. water cooling (6 m/s). We have calculated thermal parameters of the production device by FLUENT, get the data of temperature distribution gradient, hotspot, limiting temperature, uneven factor etc. We also get the effect of the equilibrium temperature from carrier gas and cooling gas. With the vertical temperature gradient in B1 axis direction under nuclear power, as shown in Fig.3, the highest temperature is 751°C, the lowest is 432°C. The distribution of temperature is influenced by neutron flux in irradiation device and small temperature difference in horizontal direction. The temperature gradually decreases from the inside of breeder area to the outside and the uneven factor is below 5%.

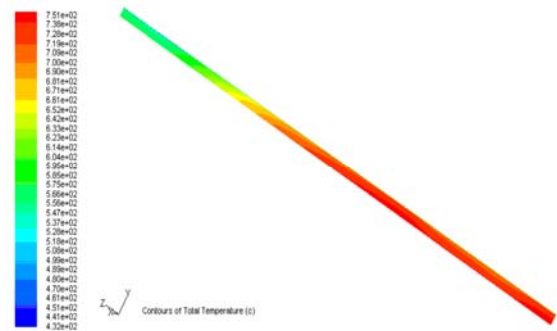


Fig.3 Distribution of temperature in B1 axis direction under nuclear power.

The maximum temperature difference is 319°C in breeder area which makes the research of tritium production and regularity of tritium release very difficult. It is necessary to set up an electric heater (asymmetry arrangement) to decrease the temperature difference in the breeder area.

There are 15 electric heat areas along with the vertical height of breeder of 750 mm, which provides

heat supplement according to heat released from breeder and can control the uneven factor to be below 5%. The maximum electric power is 18 kW which can raise equilibrium temperature up to 800°C.

4.3 Calculation of flow field parameter

Carrier-gas is the key issue of breeder replacement in the tritium production device. The pressure difference between the inlet and exit of carrier-gas pipe will produce buoyancy force on breeder sphere, and the breeder sphere will flow out the tritium production device with carrier-gas when buoyancy forces exceed the weight. This research stimulates the flow field of the tritium production device by FLUENT and gets the key process parameters through calculation and analysis of pressure distribution, flow field characteristic, buoyancy and blow force.

The tritium production device has the siphon structure, while the pressure difference between the inlet and exit is 2.06×10^6 Pa. The pressure distribution around the breeder sphere in the horn mouth is shown in Fig.4. In area 1, the pressure of carrier-gas is about 19210 Pa, in area 2, the pressure of carrier-gas is 19248 Pa. There are buoyant forces act on breeder sphere to balance the integral pressure difference between the top and bottom of sphere.

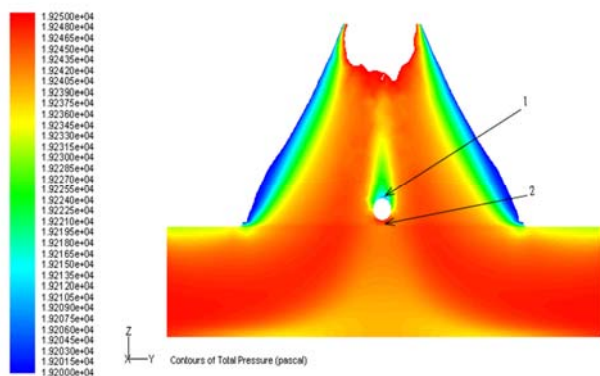


Fig.4 Pressure distribution around ball in bell-mouth.

Buoyancy force increases with the rise of pressure difference between the inlet and the exit. Buoyancy force $Y(N)$ and pressure difference $X(\text{Pa})$ is in linear relationship: $Y=2 \times 10^{-9}-3 \times 10^{-7}(1)$. When the pressure difference between the inlet and exit is more than 1.5195×10^5 Pa, buoyancy force is larger than weight. So the transmission of breeder spheres can be achieved. When the buoyancy force is 10 times larger

than weight transmission of breeder, spheres will be very easy to achieve.

5 Safety analysis of tritium production irradiation device

There are many aspects must be taken into consideration when tritium production device has been set up in the reactor. For instance, the safety of device in the $n-\gamma$ rays mixed field and hot environment, the safety of breeder in irradiation environment as well as the safety of reactor operation.

Certain calculation has been made by ANSYS to check the strength character of outer and inner irradiation cylinder. Parts of device are evaluated by stress intensity according to the Third Strength Theory. The maximum stress is 42 MPa either in normal prepared condition or in hot operating condition, which is far less than the allowable stress. Tritium production device has enough rigidity to maintain its shape and the largest deformation is 1.27×10^{-4} mm.

The highest temperature of Li_4SiO_4 spheres in operating condition has been calculated as follows: The highest temperature is 843.5°C, the average temperature is 823.5°C, which is far below the melting point of 1255°C. The temperature of outside cylinder is below 36°C when temperature of hot spot reaching the highest. The safety of irradiation tritium production device is guaranteed.

Samples and devices couldn't have any negative effect to reactor according to nuclear safety. The influencing factor to reactor has been calculated when 1132g Li_4SiO_4 loaded in B1, H4, G8 of core area and 12#, 15#, 2#, 4# channel of heavy water reflection area. Tritium production device will reduce the activity of reactor and keep ΔP in control area because of large neutron absorption section. Tritium production device would not cause any vibration, explosion and movement. All in all irradiation tritium production devices will satisfy all reactor safety in-pile irradiation.

6 Operating parameter and device characteristic

Operating parameters of tritium production device with 1 132 g Li_4SiO_4 in B1 have been confirmed as

follows: maximum neutron flux: 7.98×10^{12} n/s·cm³, external diameter of device: 63 mm, founding base: 76.2 mm×76.2 mm, maximum output of tritium: 38.34 ci/d, the temperature of the breeder core: 7 320 w, power of electric heater: 0–700 w, temperature controlling range: room temperature ~800°C, carrier-gas: He(+0.1%H₂), 0–300 ML/m, 0–0.05 MPa, exchange-gas: He, air pressure for exchange ≥ 0.05 MPa, emergency pressure ≥ 0.2 MPa, cooling-gas (He, Ne, Ar), 0.03 MPa.

Being safe, economical and multipurpose, tritium production device can achieve on-line tritium release and tritium production with either Li₄SiO₄ or other breeders meanwhile it has the capacity of realizing the research of irradiation performance, service life, neutron activity performance and diffusivity of tritium in engineering simulation field. It can also accomplish the research of effect caused by the temperature of breeder, composition of gas and flux of gas in tritium releasing field. However, the practice should be done with the on-line sampling, decreasing temperature difference of inner breeder by using nonlinear heater and it can confirm the all calculation results.

7 Conclusion

Li₄SiO₄ tritium production device is an advanced facility installed in the thermal reactor for the research of on-line tritium releasing breeder performance and technological parameters of tritium recycle. The feasibility of tritium production device has been confirmed by the simulating operation and refueling test with an irradiation capsule. Tritium production device will be an excellent platform for the basic research of tritium self sustaining and recycle in the fusion energy field.

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